



UV completion of an axial, leptophobic, Z'

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ARTICLE INFO

Article history:

Received 27 February 2020
Received in revised form 25 July 2020
Accepted 20 August 2020
Available online 25 August 2020
Editor: G.F. Giudice

ABSTRACT

The Z' -portal is one of most popular and well-explored scenarios of dark matter (DM). To avoid the strong constraints coming from dilepton resonance searches at the LHC and direct detection of DM, it is usually required that in addition to being leptophobic, the Z' is axially coupled to either the (fermionic) DM or the standard model (SM) quarks. The first possibility has been extensively studied both in the context of simplified model and ultraviolet (UV) complete scenarios. However, the studies on the second possibility are largely confined to simplified models only. Here, we construct the minimal UV completion of these models satisfying both the criteria of leptophobia and purely axial Z' -quark coupling. The anomaly cancellation conditions demand highly non-trivial structures, not only in the dark sector, but also in the Higgs sector. We also discuss the main phenomenological implications of the UV completion, in particular the existence of novel constraints associated to the $Z - Z'$ mixing, and examine the thermal DM production.

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1. Introduction

One of the most popular scenarios for dark matter (DM) consists of a Standard Model (SM) fermionic singlet, χ (the DM particle) coupled to SM fields via a massive Z' gauge boson (see e.g. [1–26]). Typically, the most severe constraints on these kinds of models come from dilepton production at the LHC [27,28] and from DM direct-detection experiments [29]. Concerning the first ones, a usual strategy is to consider leptophobic models, so that the Z' just couples to quarks in the SM sector. Similarly, spin-independent direct-detection cross-section is drastically suppressed if the Z' has axial couplings either to the DM particle or to the quarks (or both) [9,13,19,30–32].

Usually, the phenomenological analyses have been done in the context of simplified DM models, where the DM particle and the Z' mediator are the only extra fields (see e.g. [33]). The corresponding parameter-space is then spanned by the Z' -mass, its coupling to the DM particle and the coupling(s) to the SM fields.

However, the above view becomes over-simplified when one takes into account theoretical constraints, in particular those coming from the requirement of anomaly cancellation. In this sense, there have been a number of studies exploring possible ultraviolet (UV) completions of the leptophobic Z' scenario when the Z' boson has vectorial coupling to quarks and (preferably) axial coupling

to the DM particle [31,34,35]. In that case, the most important conclusion that emerges is that the dark sector (DS) has to be enlarged beyond the most simplified picture. More precisely, the minimal DS consists of the DM particle, $\chi_{L,R}$, a $SU(2)$ doublet, $\psi_{L,R}$, and a $SU(2)$ singlet, $\eta_{L,R}$. On the other hand, the charges of these fields under the extra $U(1)$ are fixed by anomaly cancellation, thus reducing the effective parameter-space; although there appear new parameters related to the extra stuff in the DS.

The complementary scenario, when the leptophobic Z' boson has purely axial coupling to the SM quarks and vectorial/axial vector coupling to the DM particle has been often considered in phenomenological analyses (usually in the context of simplified models) [9,19,30,32]; but its possible UV completions remain mostly unexplored, except for Ref. [19]. The main goal of this paper is to determine the form of the minimal DS for this scenario, consistent with anomaly cancellation, and the complete set of consistent assignments of ordinary and extra hypercharges to the various fields. We show that, as for the vectorial case, the DS must be extended with respect to the usual assumptions in simplified models; actually the extension is larger than for the vectorial case.

In addition, we show that for any, minimal or not, UV completion, the consistency of the scenario requires the Higgs sector to contain at least three Higgs doublets.

In Sec. 2 we outline the structure of the Higgs sector as required by the conditions of leptophobia and axial couplings to quarks. In Sec. 3 we derive the constraints on the particle content of the models coming from the anomaly cancellation conditions. In Sec. 4, we present the minimal scenario consistent with all the re-

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quirements, giving a complete account of the possible assignments of charges to the various fields. Sec. 5 contains a brief discussion on the main phenomenological features and constraints relevant to the UV completion. In Sec. 6 we examine the (thermal) DM production in the early universe in this scenario, as well as its consistency with the constraints discussed in the previous section. Finally, we conclude in Sec. 7.

2. Constraints in the Higgs sector

Let us start by showing that a leptophobic Z' axially coupled to quarks requires a Higgs sector consisting of, at least, three Higgs doublets. If the Higgs sector contains just one Higgs (as in the SM), then the invariance under the extra gauge factor, $U(1)_{Y'}$, of the fermionic Yukawa couplings

$$y_i^e \bar{L}_i H e_i, \quad y_i^u \bar{Q}_i \bar{H} u_i, \quad y_i^d \bar{Q}_i \bar{H} d_i \quad (1)$$

(y_i are the Yukawa coupling constants, with i a family index), forces the Y' -charge of the Higgs to vanish, $Y'_H = 0$, in order to satisfy the leptophobia assumption ($Y'_L = Y'_e = 0$). On the other hand, since $Y'_Q = -Y'_u = -Y'_d$ (axial-coupling assumption), the invariance of the above hadronic Yukawa couplings implies $Y'_{Q_i} = Y'_{u_i} = Y'_{d_i} = 0$, so there is no coupling to quarks at all.

For a two-Higgs doublet (2HDM) model things are similar. Suppose that in the 2HDM under consideration u - and d -quarks couple to the same Higgs, say H_1 . This is the case of Type I and lepton-specific 2HDMs [36]. Then, the invariance of the hadronic Yukawa couplings,

$$y_i^u \bar{Q}_i \bar{H}_1 u_i, \quad y_i^d \bar{Q}_i \bar{H}_1 d_i, \quad (2)$$

plus the axial requirement ($Y'_Q = -Y'_u = -Y'_d$) imply $Y'_{H_1} = Y'_{Q_i} = Y'_{u_i} = Y'_{d_i} = 0$.

Suppose now that d -quarks couple to a Higgs doublet, say H_1 , different to that of u -quarks, say H_2 . This is the case of Type II and flipped 2HDMs [36]. Since one of the two Higgses must couple to leptons, either $Y'_{H_1} = 0$ or $Y'_{H_2} = 0$. Then the axial condition plus the invariance of the hadronic Yukawa couplings,

$$y_i^u \bar{Q}_i \bar{H}_2 u_i, \quad y_i^d \bar{Q}_i \bar{H}_1 d_i, \quad (3)$$

imply $Y'_{H_1} - Y'_{H_2} = 0$, and thus finally all the Y' hypercharges must be vanishing in the SM sector. Consequently, the minimal number of Higgses to implement a leptophobic Z' with axial couplings to quarks is three, say H_u , H_d , H_l , each one of them coupled specifically to u -quarks, d -quarks and leptons respectively. This conclusion is completely general, independently of the UV completion of the model.

3. Constraints from anomaly cancellation

Let us now obtain the conditions that anomaly cancellation imposes on the dark sector. From now on we will assume that the $U(1)_{Y'}$ group is flavour-blind. This is a sensible assumption since, otherwise, a not-too-heavy Z' would naturally lead to dangerous FCNC. On top of that, if the $U(1)_{Y'}$ charges of u - and d -quarks are family-dependent, the off-diagonal terms of the corresponding Yukawa matrix (necessary to reproduce the observed CKM matrix) would be forbidden unless they arise from the coupling of the quarks to extra Higgs-doublets. This would lead to further extensions of the Higgs sector. Besides, the mass-eigenstates of the quarks would not have well-defined $U(1)_{Y'}$ charges, thus spoiling their axial coupling to the Z' .

Therefore, the three generations of the SM fermions transform under the gauge group, $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{Y'}$, as

$$\begin{aligned} Q & (3, 2, \frac{1}{6}, Y'_Q), \\ u_R & (3, 1, \frac{2}{3}, -Y'_Q), \\ d_R & (3, 1, -\frac{1}{3}, -Y'_Q), \\ L & (1, 2, -\frac{1}{2}, 0), \\ e_R & (1, 1, -1, 0). \end{aligned} \quad (4)$$

In addition, we will often take $Y'_Q = 1$ with no loss of generality (it entails a normalization factor for the extra hypercharge).

The first consequence of these axial $U(1)_{Y'}$ charges of quarks is that there are six new anomalies to be considered:

$$\begin{aligned} & SU(3)_C^2 \times U(1)_{Y'} \\ & SU(2)_L^2 \times U(1)_{Y'} \\ & U(1)_Y^2 \times U(1)_{Y'} \\ & U(1)_Y \times U(1)_{Y'}^2 \\ & U(1)_{Y'} \\ & U(1)_{Y'}^3. \end{aligned} \quad (5)$$

Out of them, only the fourth one is cancelled inside the SM sector. Hence, the existence of a dark sector (DS) to implement anomaly cancellation is compulsory. Since we are interested in the minimal DS able to do that job, all the DS fermions, say f , must be vectorial under the ordinary hypercharge, $U(1)_Y$, i.e. $Y_{f_L} = Y_{f_R} \equiv Y_f$, so that the four SM anomalies, $SU(3)_C^2 \times U(1)_Y$, $SU(2)_L^2 \times U(1)_Y$, $U(1)_Y^3$ and $U(1)_Y$, are kept vanishing. Otherwise, the DS has to be further increased (this holds for all the scenarios analyzed in the paper).

In order to play the role of the DM particle, the DS must contain a neutral particle, singlet under $SU(3)_C \times U(1)_{em}$. The simplest possibility is a fermion, $\chi_{L,R}$, singlet under the whole SM gauge group, $SU(3)_C \times SU(2)_L \times U(1)_Y$. Then, additional fields in the DS are needed in order to cancel the anomalies of Eq. (5); in particular those associated to $SU(3)_C^2 \times U(1)_{Y'}$ and $SU(2)_L^2 \times U(1)_{Y'}$, which require non-trivial representations under $SU(3)_C \times SU(2)_L$. Thus the cheapest option (if viable) would be to use one extra particle, say $\Gamma_{L,R}$, transforming as $(3, 2)$. However, the corresponding equations for anomaly-cancellation read

$$\begin{aligned} 12Y'_Q + 2(Y'_{\Gamma_L} - Y'_{\Gamma_R}) &= 0, \\ 9Y'_Q + 3(Y'_{\Gamma_L} - Y'_{\Gamma_R}) &= 0, \end{aligned} \quad (6)$$

which are compatible only if $Y'_Q = 0$.

Consequently, we have to incorporate additional fields to the DS. The most economical alternative is to consider, beside the DM particle $\chi_{L,R}$, one $SU(3)_C$ triplet, $\Phi_{L,R}$, and one $SU(2)_L$ doublet, $\psi_{L,R}$. Hence, the DS spectrum reads

$$\begin{aligned} \chi_L & (1, 1, 0, Y'_{\chi_L}), \\ \chi_R & (1, 1, 0, Y'_{\chi_R}), \\ \Phi_L & (3, 1, Y_\Phi, Y'_{\Phi_L}), \\ \Phi_R & (3, 1, Y_\Phi, Y'_{\Phi_R}), \\ \psi_L & (1, 2, Y_\psi, Y'_{\psi_L}), \\ \psi_R & (1, 2, Y_\psi, Y'_{\psi_R}). \end{aligned} \quad (7)$$

The corresponding cancellation conditions for the six anomalies of Eq. (5) are given by Eqs. (35) in the Appendix. We show that they only have non-trivial solution ($Y'_Q \neq 0$) if $Y_\psi = \pm 1/2$, $Y_\Phi = \pm 1/6$.

Solving the complete set of equations (35) we find the 8 possible assignments of charges for the DS, which are presented in Table A.1.

To summarize, the DS of Eq. (7) with the charges of Table A.1 represents the most economical UV completion of a leptophobic Z' with axial couplings to quarks. Nevertheless, the fact that the dark quarks (Φ) have electric charge $Q_\Phi^{\text{el}} = \pm 1/6$ strongly suggests the existence of stable baryons with fractional electric charge, e.g. $\pm 1/2$, which would be cosmologically disastrous [37,38]. Hence, we consider this possibility unrealistic.

There is another, in principle equally economical, alternative for the DS when the DM particle is the neutral component of the doublet, ψ . This requires $Y_\psi = \pm 1/2$ from the beginning. Then, one could try to satisfy the anomaly-cancellation conditions just with the addition of a $SU(3)_C$ triplet, $\Phi_{L,R}$ (to cancel the color anomaly) plus a singlet field, $\eta_{L,R}$. The corresponding spectrum of the DS is similar to the previous case:

$$\begin{aligned} &\psi_L (1, 2, Y_\psi, Y'_{\psi_L}), \\ &\psi_R (1, 2, Y_\psi, Y'_{\psi_R}), \\ &\Phi_L (3, 1, Y_\Phi, Y'_{\Phi_L}), \\ &\Phi_R (3, 1, Y_\Phi, Y'_{\Phi_R}), \\ &\eta_L (1, 1, Y_\eta, Y'_{\eta_L}), \\ &\eta_R (1, 1, Y_\eta, Y'_{\eta_R}). \end{aligned} \quad (8)$$

In this case, the cancellation conditions for the six anomalies of Eq. (5) are given in Eqs. (37) in the Appendix. There we find that there are not any non-trivial solutions ($Y'_Q \neq 0$) for which $Y_\Phi = n/3$, with n integer. Again, this suggests the existence of stable baryons with fractional electric charge, which is cosmologically unacceptable. So, we consider this possibility unrealistic as well. We have anyway worked out the complete set of equations (37), finding again 8 possible assignments of charges for the DS of Eq. (8), which are presented in Table A.2 of the Appendix.

In summary, the two minimalistic UV completions, Eqs. (7), (8), examined in this section are not phenomenologically viable, so we have to go a step forward by adding, at least, one extra $SU(3)_C \times SU(2)_L$ singlet. This leads to our final minimal scenario, which is discussed in the next section.

4. The minimal scenario

From the above discussion it follows that the minimal (viable) DS for a leptophobic mediator, Z' , axially coupled to quarks, consists of four particles: $\chi_{L,R}, \Phi_{L,R}, \psi_{L,R}, \eta_{L,R}$, with $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{Y'}$ representations:

$$\begin{aligned} &\chi_L (1, 1, 0, Y'_{\chi_L}), \\ &\chi_R (1, 1, 0, Y'_{\chi_R}), \\ &\Phi_L (3, 1, Y_\Phi, Y'_{\Phi_L}), \\ &\Phi_R (3, 1, Y_\Phi, Y'_{\Phi_R}), \\ &\psi_L (1, 2, Y_\psi, Y'_{\psi_L}), \\ &\psi_R (1, 2, Y_\psi, Y'_{\psi_R}), \\ &\eta_L (1, 1, Y_\eta, Y'_{\eta_L}), \\ &\eta_R (1, 1, Y_\eta, Y'_{\eta_R}). \end{aligned} \quad (9)$$

We have assumed here that the χ particle has vanishing hypercharge, in order to play the role of DM, but the latter could also be played by the neutral component of ψ (if $Y_\psi = \pm 1/2$).

Now the conditions for the cancellation of the six anomalies of Eq. (5) read

$$\begin{aligned} 12Y'_Q + (Y'_{\Phi_L} - Y'_{\Phi_R}) &= 0 \\ 9Y'_Q + (Y'_{\psi_L} - Y'_{\psi_R}) &= 0 \\ \frac{11}{2}Y'_{Q_L} + 3Y_\Phi^2(Y'_{\Phi_L} - Y'_{\Phi_R}) + 2Y_\psi^2(Y'_{\psi_L} - Y'_{\psi_R}) + Y_\eta^2(Y'_{\eta_L} - Y'_{\eta_R}) \\ &= 0 \\ 3Y_\Phi(Y_{\Phi_L}^2 - Y_{\Phi_R}^2) + 2Y_\psi(Y_{\psi_L}^2 - Y_{\psi_R}^2) + Y_\eta(Y_{\eta_L}^2 - Y_{\eta_R}^2) \\ &= 0 \\ 36Y'_{Q_L} + 3(Y'_{\Phi_L} - Y'_{\Phi_R}) + 2(Y'_{\psi_L} - Y'_{\psi_R}) + (Y'_{\eta_L} - Y'_{\eta_R}) \\ &+ (Y'_{\chi_L} - Y'_{\chi_R}) = 0 \\ 36Y'_{Q_L} + 3(Y_{\Phi_L}^3 - Y_{\Phi_R}^3) + 2(Y_{\psi_L}^3 - Y_{\psi_R}^3) + (Y_{\eta_L}^3 - Y_{\eta_R}^3) \\ &+ (Y_{\chi_L}^3 - Y_{\chi_R}^3) = 0. \end{aligned} \quad (10)$$

This set of equations is difficult to handle. However, it becomes much more tractable by going into a Gröbner basis for them [39]. This provides a set of equations, equivalent to (10), in which the unknowns can be trivially solved in sequential order, much as in Gaussian elimination for a system of linear equations. Normalizing the extra hypercharges as $Y'_Q = 1$, the equivalent set of equations reads

$$2Y_\eta^2(Y'_{\chi_L} - Y'_{\chi_R} - 18) + 72Y_\Phi^2 + 36Y_\psi^2 - 11 = 0 \quad (11)$$

$$Y'_{\chi_L} - Y'_{\chi_R} + Y'_{\eta_L} - Y'_{\eta_R} - 18 = 0 \quad (12)$$

$$\begin{aligned} &Y_{\chi_L}^3(-A - 72Y_\Phi^2) + Y_{\chi_R}^3(A + 72Y_\Phi^2) \\ &+ 4Y_{\chi_R}^2(-81(-3B + 8C) - 36Y'_{\eta_R}(C - A) + Y_{\eta_R}^2 A) \\ &+ 2Y_{\chi_R}^2(-9(-3B + 4C) - Y'_{\eta_R} D) \\ &- Y_{\chi_L}^2(-3Y_{\chi_R}^2 B + 2(9(4C - 3B) + Y'_{\eta_R} D)) \\ &+ Y_{\chi_L}^2(-3Y_{\chi_R}^2 B + 4Y_{\chi_R}^2(9(4C - 3B) + Y'_{\eta_R} D) \\ &+ 4(81(8C - 3B) - Y_{\eta_R}^2 A + 36Y'_{\eta_R}(C - A))) \\ &+ 72(-18Y_{\eta_R}^2(2C - A) + Y_{\eta_R}^2 A \\ &+ 3(8Y_\Phi^2(70 - 27Y'_{\psi_R} + 3Y_{\psi_R}^2) \\ &- 3(99 + 36C + (-405 + 36Y_{\psi_R} - 4Y_{\psi_R}^2)) = 0 \end{aligned} \quad (13)$$

$$Y'_{\psi_L} - Y'_{\psi_R} + 9 = 0 \quad (14)$$

$$\begin{aligned} &(Y'_{\chi_R} + Y'_{\eta_R} + 18)(Y'_{\chi_L} - Y'_{\chi_R})(Y'_{\eta_R} - Y'_{\chi_L} + 18) \\ &+ 18(2Y_{\Phi_R}(Y'_{\Phi_R} - 12) + Y'_{\psi_R}(Y'_{\psi_R} - 9) - Y'_{\eta_R}(Y'_{\eta_R} + 18)) \\ &+ 258 = 0 \end{aligned} \quad (15)$$

$$Y'_{\Phi_L} - Y'_{\Phi_R} + 12 = 0, \quad (16)$$

with

$$\begin{aligned} A &= -11 + 36Y_\psi^2 \\ B &= A - 24Y_\Phi^2 \\ C &= Y_\eta(-9 + 2Y'_{\psi_R})Y_\psi \\ D &= 22 - 72Y_\psi^2. \end{aligned} \quad (17)$$

The free (arbitrary) parameters in the previous equations (11)–(16) are

$$\{Y_\eta, Y_\psi, Y_\Phi, Y'_{\chi_R}, Y'_{\eta_R}\}. \quad (18)$$

Table 1

Explicit examples of extra-hypercharge assignments in the minimal DS, Eq. (9), that lead to anomaly cancellation. (For the non-rational charges, only the first decimals are shown.) The extra-hypercharges of the SM quarks, Eq. (4), are normalized as $Y'_Q = 1$. The ordinary hypercharges of the DS fermions are $Y_\eta = 1$, $Y_\psi = 1/2$ and $Y_\Phi = 1/3$.

Y'_{χ_R}	1	1	1	1	2	2
Y'_{η_R}	1	1	2	2	1	1
Y'_{χ_L}	16	16	16	16	17	17
Y'_{η_L}	4	4	5	5	4	4
Y'_{ψ_R}	0.260	9.621	0.404	9.830	-0.440	10.323
Y'_{ψ_L}	-8.739	0.621	-8.595	0.830	-9.440	1.323
Y'_{Φ_R}	9.804	2.783	9.946	2.877	10.330	2.257
Y'_{Φ_L}	13.045	10.705	13.982	11.625	13.221	10.530

This means, in particular, that we can freely choose all the ordinary hypercharges of the DS, so that there are no cosmological problems related to fractional electric charges. Now, each equation in (11)–(16) solves one parameter in terms of the precedent ones, so it is trivial, once the initial parameters (18) have been chosen, to obtain the others in terms of them. The sequence of reduction goes as

$$\{Y_\eta, Y_\psi, Y_\Phi, Y'_{\chi_R}, Y'_{\eta_R}\} \rightarrow Y'_{\chi_L} \rightarrow Y'_{\eta_L} \rightarrow Y'_{\psi_R} \rightarrow Y'_{\psi_L} \rightarrow Y'_{\Phi_R} \rightarrow Y'_{\Phi_L}. \quad (19)$$

Note that for all the equations the eliminations are linear, and thus completely trivial and unambiguous, except for Eq. (13), which is a second-order equation and therefore implies a double solution for Y'_{ψ_R} (and thus for the subsequent variables in the sequence (19)).

Eqs. (11)–(16) represent the general solution for the possible hypercharges and extra-hypercharges of the minimal DS (9). In order to gain some intuition on the scenario we can particularize the general solution for sensible values of the hypercharges. E.g. for $Y_\eta = 1$, $Y_\psi = 1/2$, $Y_\Phi = 1/3$, we get¹

$$Y'_{\chi_L} - Y'_{\chi_R} - 15 = 0 \quad (20)$$

$$-3 + Y'_{\eta_L} - Y'_{\eta_R} = 0 \quad (21)$$

$$371 - 300Y'_{\chi_R} - 20Y'^2_{\chi_R} + 78Y'_{\eta_R} - Y'^2_{\eta_R} - 486Y'_{\psi_R} - 18Y'_{\eta_R}Y'_{\psi_R} + 51Y'^2_{\psi_R} = 0 \quad (22)$$

$$9 + Y'_{\psi_L} - Y'_{\psi_R} = 0 \quad (23)$$

$$-39 - Y'_{\eta_R} + 4Y'_{\Phi_R} + 3Y'_{\psi_R} = 0 \quad (24)$$

$$-9 - Y'_{\eta_R} + 4Y'_{\Phi_L} + 3Y'_{\psi_R} = 0, \quad (25)$$

with the same sequence of reduction as (19). Some particular solutions to Eqs. (20)–(25) are shown in Table 1. Unfortunately some of the Y' -charges seem to be typically non-rational, at least we have not found a fully-rational solution to Eqs. (20)–(25).

One could try to get additional examples of UV completion by going beyond the minimal DS studied in this paper. One possibility, examined in Ref. [19], is to consider a DS consisting of a whole SM-like vectorial family. In this way, a model (named Model 4) was obtained in [19] with rational (though still weird) extra-hypercharges.

Another (even less economical, but somehow trivial) solution is to assign to every SM fermion a DS fermion with the same representation and charges, but opposite chirality. In this way all

fermions form vectorial pairs and anomaly cancellation is automatic. This obvious possibility was also noticed in Ref. [19]. Then the DM fermion, $\chi_{L,R}$, must correspond to a couple of right-handed neutrinos with non-vanishing extra-hypercharge. Besides, the Higgs sector must be further extended to incorporate Yukawa couplings for both charged and neutral leptons. Notice also that in a scenario of this kind, the remarkable anomaly cancellation inside the ordinary SM would be a (weird) accident.

5. Phenomenological perspective

In this section we examine, from a phenomenological point of view, the main differences between the simplified model approaches (e.g. [9,30,32]) and the UV-complete scenario of an axial, leptophobic Z' described by the most minimal scenario of Sec. 4. We focus on the appearance of additional phenomenological constraints, which will be taken into account in the next section for the analysis of the DM production in the early universe.

5.1. Kinetic mixing

The presence of an extra $U(1)$ interaction opens the door to a dangerous kinetic mixing between the standard B -boson and the one associated to $U(1)_{Y'}$,

$$\mathcal{L}_{\text{kin}} \supset -\frac{1}{2} \epsilon F_{\mu\nu}^Y F^{Y'\mu\nu}. \quad (26)$$

This mixing contributes to the S and T parameters and, most importantly, to dilepton production at the LHC. One can set $\epsilon = 0$ at some scale Λ (presumably the scale of symmetry breaking of a unifying gauge group), but still the mixing is radiatively generated through loops involving particles with non-vanishing Y, Y' charges. In the case of a Z' with vectorial coupling to quarks, the contribution of the latter is $\Delta\epsilon \simeq 0.02 g_{Y'} Y'_Q \log \Lambda/\mu$, where $\mu \sim M_{Z'}$ [13]. This translates in bounds on the gauge coupling. E.g. for $\Lambda = 10$ TeV and $M_{Z'} = 200$ GeV (1 TeV) one gets $g_{Y'} Y'_Q < 0.1$ (1) [13]. As it was pointed out in Ref. [13], in the case of axial coupling the quarks do not contribute to the mixing, since their contributions cancel as a consequence of $\text{Tr } Y = 0$ in the quark sector, see Eq. (4). However, the dark leptons, whose presence is obliged in the UV completion, do contribute to the mixing, namely

$$\begin{aligned} \Delta\epsilon &= \frac{eg_{Y'}}{12\pi^2 \cos\theta_W} [2Y_\psi(Y'_{\psi_L} - Y'_{\psi_R}) + 3Y_\Phi(Y'_{\Phi_L} - Y'_{\Phi_R}) \\ &\quad + (Y'_{\eta_L} - Y'_{\eta_R})] \log \Lambda/\mu \\ &\simeq 0.003 \mathcal{O}(10) g_{Y'} \log \Lambda/\mu, \end{aligned} \quad (27)$$

where we have used the values of the charges of Table 1. Note that the extra hypercharges, Y'_{ψ_L}, Y'_{ψ_R} , etc. depend on the model but they are always $\mathcal{O}(10)$ due to the anomaly cancellation conditions. Consequently, in contrast to previous simplified analyses, for the axial case it continues to be true that a kinetic mixing is generated with a similar size as in the vectorial instance. It is also worth-noticing that the presence of two Higgs doublets, H_u, H_d with non-vanishing Y, Y' charges (see Sec. 2) does potentially contribute to ϵ . Nevertheless, the fact that they possess the same (opposite) Y (Y') charge makes their contributions to cancel.

5.2. Mass mixing

The presence of the two Higgs doublets, H_u, H_d , with non-vanishing Y, Y' charges does lead however to a mixing term in the $Z - Z'$ mass matrix,

$$M_{Z-Z'}^2 = \begin{pmatrix} M_{Z^0}^2 & \Delta^2 \\ \Delta^2 & M_{Z'}^2 \end{pmatrix}. \quad (28)$$

¹ The set of equations (20)–(25) is of course equivalent to the set (11)–(16) for these values of Y_η, Y_ψ, Y_Φ . However we have obtained them by replacing those values in the initial equations (10) and then going into a Gröbner basis.

The off-diagonal term is given by

$$\Delta^2 = \frac{1}{2} \sqrt{g^2 + g'^2} g_{Y'} Y'_H (v_u^2 - v_d^2) \\ = -\sqrt{g^2 + g'^2} g_{Y'} \cos 2\beta \tilde{v}^2, \quad (29)$$

where $Y'_H = Y'_{H_u} = Y'_{H_d} = 2Y'_Q = 2$ and $\langle H_u \rangle = \frac{1}{\sqrt{2}}(0, v_u)$, $\langle H_d \rangle = \frac{1}{\sqrt{2}}(v_d, 0)$, $\langle H_l \rangle = \frac{1}{\sqrt{2}}(v_l, 0)$, with $v^2 = v_u^2 + v_d^2 + v_l^2 = (246 \text{ GeV})^2$. Furthermore we have defined $\tilde{v}^2 = v_u^2 + v_d^2$ and $v_u = \tilde{v} \sin \beta$, $v_d = \tilde{v} \cos \beta$. Note that \tilde{v} cannot be much smaller than v , otherwise the top Yukawa coupling would become non-perturbative. Since $\Delta^2 \ll M_{Z^0}^2, M_{Z'}^2$, we can approximate the diagonal entries in Eq. (28) to the actual mass eigenvalues.

Now, the mixing angle, θ , between the two neutral vector bosons, Z, Z' is given by

$$\theta = \arctan \frac{\Delta^2}{M_{Z^0}^2 - M_{Z'}^2} \simeq \frac{\sqrt{g^2 + g'^2} g_{Y'} \cos 2\beta \tilde{v}^2}{M_{Z'}^2}, \quad (30)$$

where we have used $M_{Z^0}^2 \ll M_{Z'}^2$ and $\theta \ll 1$.

It should be noted that this source of mixing is totally model-independent, since the presence of the two Higgs states in the quark sector with non-vanishing Y, Y' charges is a direct consequence of the axial coupling (see Sec. 2). As a matter of fact, this contribution to the mixing can be more important than that from the previous kinetic mixing. The current limits on θ relevant for us come from electroweak precision tests [40,41] and resonant WW [42–47] production at the LHC. Typically the bounds are at the per mil level. Hence, Eq. (30) implies a lower bound on $M_{Z'}$,

$$M_{Z'} \gtrsim (g^2 + g'^2)^{1/4} \sqrt{\frac{g_{Y'} \cos 2\beta}{\theta_{\max}}} \tilde{v} \simeq 27 \sqrt{g_{Y'} \cos 2\beta} \tilde{v}, \quad (31)$$

where we have used $|\theta_{\max}| = 10^{-3}$. We will apply the bound (31) in the next section.

5.3. Perturbativity limits

The large Y' charges in the minimal dark sector, required for anomaly cancellation, impose perturbativity limits on $g_{Y'}$. Although the particular values depend upon the model (see Table 1), there exist some regularities. In particular, the largest difference between the left and right extra hypercharges corresponds to the dark matter: $Y'_{\chi_L} - Y'_{\chi_R} = 15$, which suggests the presence of a scalar with charge $Y'_S = 15$ to provide mass to the dark matter. Since the perturbative regime requires $Y'_S g_{Y'} \leq 4\sqrt{\pi}$ (see Ref. [48] for a detailed discussion), we conclude that

$$g_{Y'} \lesssim 1/2. \quad (32)$$

On the other hand, the Yukawa couplings responsible for the DM mass are also subject to perturbativity constraints. E.g. assuming that the DM mass arises from a Dirac Yukawa coupling, $y_\chi \bar{\chi} S \chi$, so that $M_\chi = y_\chi \langle S \rangle$, and taking into account that $M_{Z'} \geq \sqrt{2} Y'_S g_{Y'} \langle S \rangle$ (the equality occurs when $\langle S \rangle$ is the dominant contribution to $M_{Z'}$), the perturbative limit $y_\chi \leq 4\sqrt{\pi}$ translates into an upper bound on M_χ ,

$$M_\chi \lesssim \frac{\sqrt{8\pi}}{Y'_S g_{Y'}} M_{Z'}. \quad (33)$$

5.4. Extra scalars

The phenomenological viability of the minimal dark sector requires the presence of several extra scalar fields. First of all, there must be one (or several) scalar(s) responsible for the $U(1)_{Y'}$ breaking. Certainly, the obliged presence of at least three Higgs states, H_u, H_d, H_l allows in principle to give mass to the Z' without any extra scalar state. However, this would imply unacceptably large $Z - Z'$ mixings unless the coupling becomes negligibly small. Consequently, one extra scalar, S , is required to play the dominant role in the $U(1)_{Y'}$ breaking. Besides, its VEV (times Y'_S) must be much larger than those of the Higgses, to avoid too large off-diagonal entries in the $Z - Z'$ mass matrix, as discussed above.

The mass of this scalar is restricted by unitarity, see Ref. [13],

$$M_S \lesssim \frac{\pi M_{Z'}^2}{g_f^2 M_f}, \quad (34)$$

where f is the heaviest fermion in the theory with axial coupling, g_f^A , to Z' . In particular $g_f^A = g_{Y'} Y'_Q$ for the top quark and $g_f^A = g_{Y'} (Y'_{f_R} - Y'_{f_L})/2$ for the dark fermions.

Notice also that scalar fields are required to give masses to the dark fermions: χ, ψ, η, Φ . The fact that their Y' charges are not the same implies the presence of at least 4 extra scalars in the model.

6. Dark matter abundance

In this section we examine the (thermal) DM production in the early universe in this scenario, as well as its consistency with the constraints discussed in the previous section.

The most obvious modification of the DM phenomenology induced by the UV completion of the model is the role played by the extra scalar, S , and the dark fermions in DM annihilation (the first issue was partially addressed in Ref. [13]). More precisely, the presence of extra fermions with non-trivial representation under the SM gauge group can induce co-annihilation effects if their masses are not far from the DM one. Admittedly, this is a model-dependent issue. However, even under the simplifying assumption that the masses of the extra fermions (except the DM one) are large enough to play no role, the dark matter phenomenology becomes interesting. This study addresses a relevant portion of the parameter space of the theory. Of course, the case corresponds to a “simplified DM model” (see Sec. 1), where only the DM and the mediator particles (and sometimes the scalar responsible for the breaking of $U(1)_{Y'}$) are taken into account, which is the usual framework of previous phenomenological analyses. The important difference here from previous “simplified model” analyses is that there is now a correlation between the couplings of the Z' to the DM, the scalar and the SM fields. In addition, there is an unavoidable $Z - Z'$ mixing, as discussed in section 5.

In the simplified scenario just depicted, the main annihilation channels of DM come from the diagrams of Fig. 1 (in the case of $M_S > 2M_\chi$, only the first two are relevant). In the following, for the sake of definiteness, we will consider the model shown in the first column of Table 1, but the results for the other models are similar since the value of Y'_S is the same in all the cases and Y'_{χ_L}, Y'_{χ_R} are also alike (the other dark fields are irrelevant in the limit considered). In addition, we will assume that the DM field, χ , gets its mass from a Dirac Yukawa coupling, just as discussed before in Eq. (33).

Clearly, the annihilation rate depends on three parameters: $\{g_{Y'}, M_{Z'}, M_\chi\}$, and additionally on M_S if the S -field plays a relevant role. Consequently, for each choice of $\{M_{Z'}, M_\chi, M_S\}$ there is always a (unique) value of $g_{Y'}$ leading to the correct relic DM density, $\Omega_{\text{DM}} h^2 = 0.120 \pm 0.001$ [49]. This is illustrated in Fig. 2 for

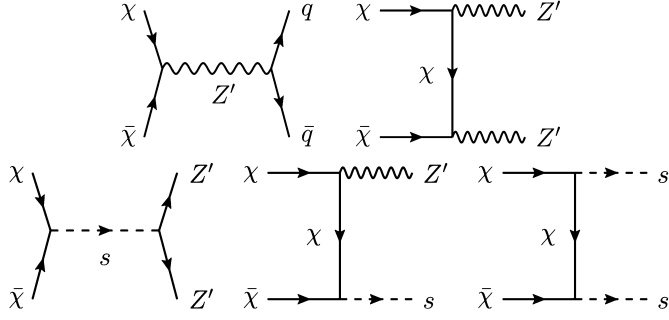
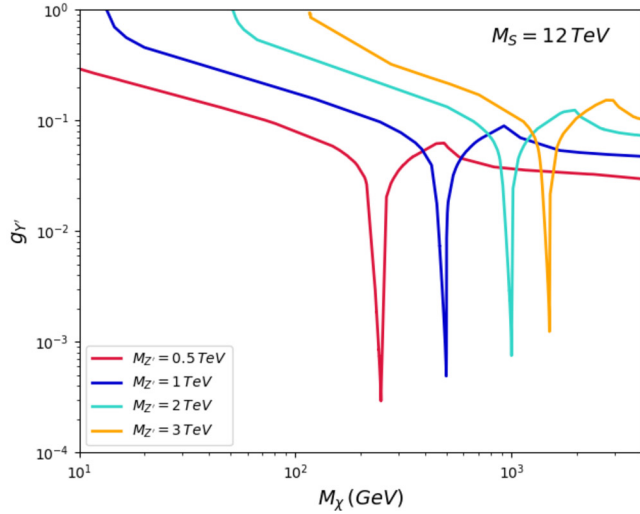


Fig. 1. Relevant Feynman diagrams for DM annihilation.

several choices of $M_{Z'}$ and two choices of the scalar mass, namely $M_S = 12$ TeV (i.e. irrelevant to DM annihilation) and $M_S = 2$ TeV. The calculation of the DM relic density has been performed using *MicroMEGAS* [50] which uses *CalcHEP* [51] to compute the tree level cross sections for DM annihilations. We used *FeynRules* [52,53] to implement our model in *CalcHEP* format. The results for any $M_S > 2M_\chi$ would be essentially the same as those of the first panel. Note also that $g_{Y'}$ remains in the perturbative regime



in most of the parameter space. The resonances at $2M_\chi = M_{Z'}, M_S$ are clearly visible.

Fig. 3 shows the parameter space in the $M_{Z'} - M_\chi$ plane (in the two regimes of M_S) satisfying DM relic density constraint. Recall that at each point there is a unique value of $g_{Y'}$ that reproduces the relic density, so in principle the whole plane would be allowed by the relic density constraints (cyan area). On top of this we have taken into account the constraints discussed in section 5. Namely, we have shaded in green the region where $g_{Y'}$ or the Yukawa coupling of χ fall in the non-perturbative regime, and in magenta the regions excluded by a too large $Z - Z'$ mixing, according to the bound of Eq. (31). For the latter we have conservatively assumed $\cos 2\beta = 1$ and a sizeable value $\tilde{v} = 200$ GeV. (The other constraints discussed in the previous section are always weaker than these ones and are not represented in the figure.) Still one can see that there is a substantial area allowed by the constraints.

7. Conclusions

The Z' -portal is one of most popular and well-founded scenarios of dark matter (DM). However, it is subject to severe experimental and observational constraints, in particular those coming

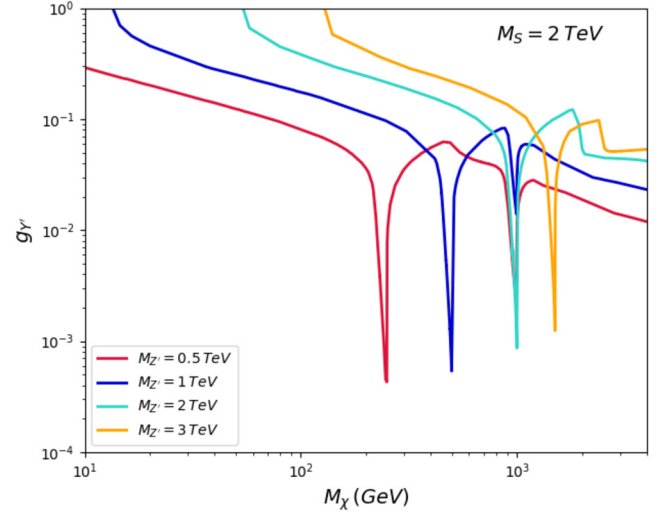


Fig. 2. Contours in the $M_\chi - g_{Y'}$ plane that reproduce the observed DM relic density for several choices of $M_{Z'}$ and two regimes of the scalar mass. The model corresponds to the first column of Table 1, but the results are similar for other models, see text for further details.

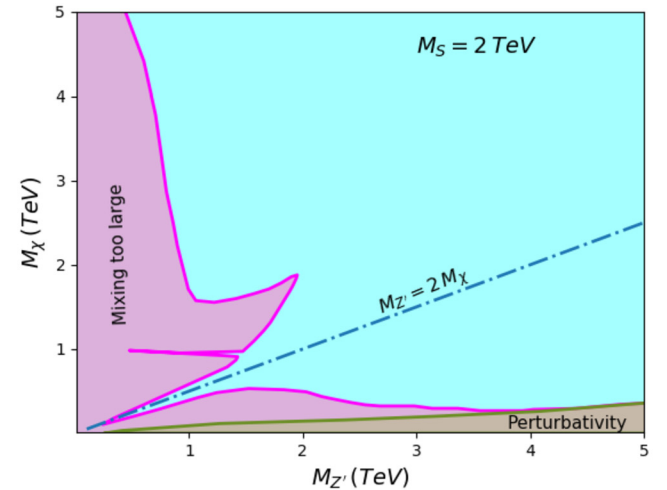
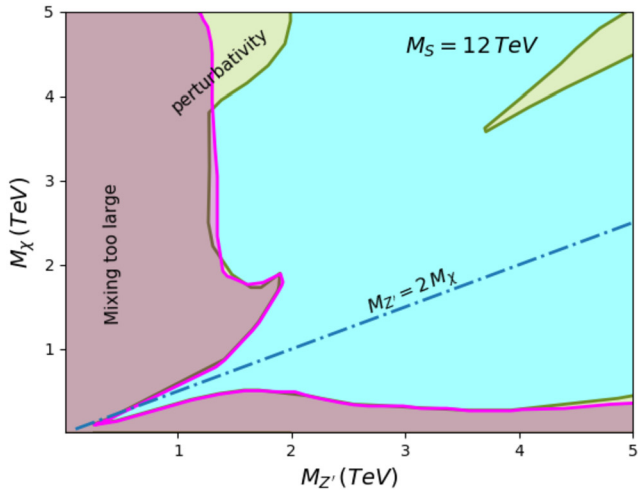


Fig. 3. For each point in the $M_{Z'} - M_\chi$ plane there is a value of $g_{Y'}$ that yields the correct relic density (cyan area). Some regions, however, are excluded by perturbativity (green area) or constraints associated to the $Z - Z'$ mixing (magenta area).

from dilepton production at the LHC and from DM direct-detection experiments. Consequently, it is often required that the Z' boson has couplings which are (i) leptophobic, (ii) axial either with the DM particle or with the quarks (or both). Condition (ii) leads to spin-dependent direct-detection cross-section, maybe with velocity suppression.

Most of the analyses along this line have so far been performed in the context of simplified models. However, it is important to consider their possible UV completions, not only for the sake of theoretical consistency but also from the phenomenological point of view. For example, the requirement of anomaly cancellation implies the existence of an extended dark sector (beyond a lone DM particle) and strong correlations between the $U(1)_{Y'}$ charges of the SM and the dark sector (DS) fermions. This is of great importance for phenomenological analyses, as well as for evaluations of the relic density.

Concerning UV completions, the case in which the leptophobic Z' has axial couplings to the DM has been well-studied in the current literature. However, the complementary case, when the Z' presents axial couplings to the quarks is still essentially unexplored (except for Ref. [19]). In this paper we have considered the latter scenario, building up the minimal DS (from the point of view of the spectrum) that is anomaly-free and contains a good candidate for DM. It turns out that the most economical possibilities are not phenomenologically viable since they contain fractional electrically-charged particles. Thus, the minimal DS consists of four particles: a SM singlet (the DM particle, $\chi_{L,R}$), a $SU(3)_C$ triplet ($\Phi_{L,R}$), a $SU(2)_L$ doublet ($\psi_{L,R}$) and a $SU(3)_C \times SU(2)_L$ singlet ($\eta_{L,R}$), see Eq. (9). This means, in particular, that the minimal DS is larger than the analogous one when the Z' has vectorial coupling to quarks.

Regarding the possible assignments of (ordinary and extra) charges to the various fields, the complete set of solutions to the anomaly-cancellation conditions can be expressed in a convenient form using a Gröbner basis, as explained in Eqs. (11)–(19). It turns out, in particular, that it is possible to choose the hypercharges of the DS fields, so that states with fractional electric-charge are absent. Then the consistency equations become simpler. Still, the set of solutions contains two free parameters, which we have chosen as Y'_{χ_R}, Y'_{η_R} , as indicated in Eq. (19). However, the solutions imply the existence of non-rational $U(1)_{Y'}$ charges. Some examples are given in Table 1. Going beyond the minimal DS it is possible to get rational (but still somewhat weird) charges.

Concerning the Higgs sector, we have shown that the consistency of Yukawa couplings requires at least three Higgs states giving mass to u -quarks, d -quarks and charged leptons, respectively. This result holds for any consistent (minimal or not) DS.

We have also described the key features of the phenomenology of the UV complete scenario as compared to its simplified-model counterparts. We noticed that, unlike the quarks, the extra (dark) fermions do contribute to the kinetic $Z - Z'$ mixing, in an amount similar to that of vectorial models, see Eq. (27). In addition, the presence of multiple Higgs bosons charged under $U(1)_{Y'}$ gives rise to a significant and model-independent contribution to the $Z - Z'$ mass mixing, see Eq. (30). Then, the existence of stringent experimental bounds on the $Z - Z'$ mixing angle can be translated into a lower limit on M'_Z as a function of the Higgs VEVs, see Eq. (31).

We have checked that these models easily reproduce the correct relic density in vast areas of the parameter space, though some regions are excluded by the previously-mentioned bounds on $Z - Z'$ mass mixing and/or perturbativity limits.

Let us finally stress that the extra dark fermions require the existence of extra scalar fields to provide appropriate masses. If not too heavy, all these fields can induce notable changes in the phenomenology of the model, in particular, they can drive DM co-

annihilation. A detailed analysis of this issue is however beyond the scope of the present paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work has been partially supported by MINECO, Spain, under contract FPA2016-78022-P and Centro de excelencia Severo Ochoa Program under grant SEV-2016-0597. We thank J.M. Moreno for illuminating discussions concerning the Gröbner basis.

Appendix A

In this appendix we summarize the charge assignments for the smallest UV completions of an axial, leptophobic Z' model, which fulfil anomaly cancellation. These were discussed in Sec. 3, where it was stressed that these “minimalistic” solutions have the shortcoming of involving particles with fractional electric charges, so they are not phenomenologically viable (the minimal phenomenologically acceptable solution is discussed in Sec. 4).

One set of such solutions corresponds to the matter content of the dark sector as given by Eq. (7). The corresponding cancellation conditions for the six anomalies of Eq. (5) read

$$\begin{aligned} 12Y'_Q + (Y'_{\Phi_L} - Y'_{\Phi_R}) &= 0 \\ 9Y'_Q + (Y'_{\psi_L} - Y'_{\psi_R}) &= 0 \\ \frac{11}{2}Y'_Q + 3Y'^2_{\Phi}(Y'_{\Phi_L} - Y'_{\Phi_R}) + 2Y'^2_{\psi}(Y'_{\psi_L} - Y'_{\psi_R}) &= 0 \\ 3Y_{\Phi}(Y'^2_{\Phi_L} - Y'^2_{\Phi_R}) + 2Y_{\psi}(Y'^2_{\psi_L} - Y'^2_{\psi_R}) &= 0 \\ 36Y'_Q + 3(Y'_{\Phi_L} - Y'_{\Phi_R}) + 2(Y'_{\psi_L} - Y'_{\psi_R}) + (Y'_{\chi_L} - Y'_{\chi_R}) &= 0 \\ 36Y'^3_Q + 3(Y'^3_{\Phi_L} - Y'^3_{\Phi_R}) + 2(Y'^3_{\psi_L} - Y'^3_{\psi_R}) \\ + (Y'^3_{\chi_L} - Y'^3_{\chi_R}) &= 0 \end{aligned} \quad (35)$$

It is worth-noticing that the first three equations imply

$$Y'_Q(72Y'^2_{\Phi} + 36Y'^2_{\psi} - 11) = 0, \quad (36)$$

which only has non-trivial solution ($Y'_Q \neq 0$) if $Y_{\psi} = \pm 1/2$, $Y_{\Phi} = \pm 1/6$. Solving the complete set of equations (35) we find the 8 possible assignments of charges for the DS presented in Table A.1. Note there that all charges are given in terms of two parameters, Y'_Q and Y'_{ψ_R} , which are arbitrary. Furthermore, as mentioned

Table A.1

Charge assignments for the DS of Eq. (7) satisfying anomaly cancellation conditions of Eq. (35). Y'_{ψ_R} is a free parameter. The expressions correspond to the normalization $Y'_Q = 1$. In general, one should understand Y'_f above as Y'_f/Y'_Q for all fermions f (including Y'_{ψ_R} inside the expressions). The two \pm signs are correlated, so for each value of Y'_{ψ_R} there are 8 solutions.

Y_{ψ}	1/2	1/2	-1/2	-1/2
Y_{Φ}	1/6	-1/6	1/6	-1/6
Y'_{Φ_R}	$\frac{3}{4}(17 - 2Y'_{\psi_R})$	$-\frac{3}{4}(1 - 2Y'_{\psi_R})$	$-\frac{3}{4}(1 - 2Y'_{\psi_R})$	$\frac{3}{4}(17 - 2Y'_{\psi_R})$
Y'_{Φ_L}	$\frac{3}{4}(1 - 2Y'_{\psi_R})$	$-\frac{3}{4}(17 - 2Y'_{\psi_R})$	$-\frac{3}{4}(17 - 2Y'_{\psi_R})$	$\frac{3}{4}(1 - 2Y'_{\psi_R})$
Y'_{ψ_L}	$Y'_{\psi_R} - 9$			
Y'_{χ_R}	$-9 \pm \frac{1}{2}\sqrt{22Y'^2_{\psi_R} - 198Y'_{\psi_R} + 2747/6}$			
Y'_{χ_L}	$9 \pm \frac{1}{2}\sqrt{22Y'^2_{\psi_R} - 198Y'_{\psi_R} + 2747/6}$			

Table A.2

Charge assignments for the DS of Eq. (8) satisfying anomaly cancellation conditions of Eq. (37), with $\Sigma = \frac{1}{2\sqrt{6}}\sqrt{(18Y_\eta^2 + 1)(132Y_{\psi_R}^2 - 1188Y'_{\psi_R} + 2747)}$. The free parameters are Y_η, Y'_{ψ_R} . For each choice of them, the remaining charges are obtained recursively following the order of the table. In each column the \pm signs are not correlated, thus leading to 8 solutions in total. As for Table A.1 the normalization $Y'_Q = 1$ has been assumed.

Y_ψ	$1/2$	$-1/2$
Y_Φ	$\pm \frac{1}{6}\sqrt{18Y_\eta^2 + 1}$	$\pm \frac{1}{6}\sqrt{18Y_\eta^2 + 1}$
Y'_{ψ_L}	$Y'_{\psi_R} - 9$	$Y'_{\psi_R} - 9$
Y'_{η_R}	$\pm \Sigma - 9Y_\eta Y'_{\psi_R} + (81Y_\eta/2 - 9)$	$\pm \Sigma - 9Y_\eta Y'_{\psi_R} + (81Y_\eta/2 - 9)$
Y'_{η_L}	$\frac{1}{2Y_\eta^2} (Y_\eta^2 Y'_{\eta_R} + 72(Y_\eta^2 - 2))$	$\frac{1}{2Y_\eta^2} (Y_\eta^2 Y'_{\eta_R} + 72(Y_\eta^2 - 2))$
Y'_{Φ_R}	$\frac{1}{72Y_\Phi} (Y_\eta(Y_{\eta_L}^2 - Y_{\eta_R}^2) + 9((48Y_\Phi + 9) - 2Y'_{\psi_R}))$	$\frac{1}{72Y_\Phi} (Y_\eta(Y_{\eta_L}^2 - Y_{\eta_R}^2) + 9((48Y_\Phi - 9) + 2Y'_{\psi_R}))$
Y'_{Φ_L}	$Y'_{\Phi_R} - 12$	$Y'_{\Phi_R} - 12$

above, there is a trivial factor of proportionality for all Y' -charges, so we have taken $Y'_Q = 1$ with no loss of generality.

As discussed in Sec. 3, the fact that the dark quarks (Φ) have electric charge $Q_\Phi^{\text{el}} = \pm 1/6$ strongly suggests the existence of stable baryons with fractional electric charge, with disastrous cosmological consequences. Thus, we consider this possibility unrealistic.

The other set of such solutions corresponds to the dark sector of Eq. (8), with $Y_\psi = \pm 1/2$ to enable a DM particle. In this case, the cancellation conditions for the six anomalies of Eq. (5) read

$$\begin{aligned}
 12Y'_Q + (Y'_{\Phi_L} - Y'_{\Phi_R}) &= 0 \\
 9Y'_Q + (Y'_{\psi_L} - Y'_{\psi_R}) &= 0 \\
 \frac{11}{2}Y'_Q + 3Y_\Phi^2(Y'_{\Phi_L} - Y'_{\Phi_R}) + 2Y_\psi^2(Y'_{\psi_L} - Y'_{\psi_R}) \\
 &+ Y_\eta^2(Y'_{\eta_L} - Y'_{\eta_R}) = 0 \\
 3Y_\Phi(Y_{\Phi_L}^2 - Y_{\Phi_R}^2) + 2Y_\psi(Y_{\psi_L}^2 - Y_{\psi_R}^2) \\
 &+ Y_\eta(Y_{\eta_L}^2 - Y_{\eta_R}^2) = 0 \\
 36Y_Q^3 + 3(Y_{\Phi_L}^3 - Y_{\Phi_R}^3) + 2(Y_{\psi_L}^3 - Y_{\psi_R}^3) \\
 &+ (Y_{\eta_L}^3 - Y_{\eta_R}^3) = 0 \\
 36Y'_Q + 3(Y'_{\Phi_L} - Y'_{\Phi_R}) + 2(Y'_{\psi_L} - Y'_{\psi_R}) + (Y'_{\eta_L} - Y'_{\eta_R}) &= 0.
 \end{aligned} \tag{37}$$

It is straightforward to check that the first five equations lead to

$$Y'_Q(72Y_\Phi^2 + 36Y_\psi^2 - 36Y_\eta^2 - 11) = 0. \tag{38}$$

Keeping in mind that $Y_\psi = \pm 1/2$, it is easy to see that this equation does not have non-trivial solutions ($Y'_Q \neq 0$) for which $Y_\Phi = n/3$, with n integer. Again, this suggests the existence of stable baryons with fractional electric charge, which is cosmologically unacceptable. So, we consider this possibility unrealistic as well.

Nevertheless, we have found the complete set of solutions, namely the 8 possible assignments of charges presented in Table A.2.

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